Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

STUDY ON MECHANISM OF LOAD TRANSFER IN PILE-RAFT FOUNDATION

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Abstract. The growth of urban infrastructure has forced the introduction of tall buildings under any subsoil condition. Many a times, pile foundation becomes an absolute choice causing increased cost of construction. In such situations, pile-raft foundation can be a convenient alternative, wherein, the raft also contributes towards a part of the load transfer and hence number of piles required can be reduced. This results in reducing the total foundation cost leading towards sustainable solution. Many tall towers across the globe have been built on Pile raft foundations and they are performing successfully. The present paper focuses on assessing the load transfer mechanism of Pile-raft foundation. For this purpose, PLAXIS, 3-D software is used. Pile raft foundation system is idealized as a continuum. The soil is modelled using Mohr–Coulomb criteria and structural components of the foundation system are modelled as rigid, elastic, concrete structures. The objective of the present paper is to identify the mechanism of load transfer and hence to arrive at the total load carrying capacity of the system. Here, an attempt is made to explain how the load is transferred to the soil from Pile-raft foundation system and an attempt is also made to identify the conditions under which Pile-raft foundation becomes more appropriate.

Keywords: Pile-raft Foundation, Group Piles, Finite Element Analysis, PLAXIS-3D, Mechanism of load transfer

1. INTRODUCTION:

Pile foundations are the most popular forms of deep foundations used for both onshore and offshore structures. They are often used to support high rise buildings resting on weak soil layers. In the recent days, the concept of Pile-Raft foundation has become very popular for tall towers. Petronas Tower in Kualalampur, Burj-Khalifa in Dubai and Messeturm building in Frankfurt are a few of the landmark tall towers built on Pile Raft foundations. The research study indicates that Pile-Raft foundation is a more economical design approach compared with Pile foundation. In pile foundations, total load from the superstructure is transferred through pile cap to soil through bearing piles. In the piled raft foundation, the pile cap itself acts as raft and rests on the ground. Hence, some amount of load is transferred through raft to the soil and the remaining load is transferred through piles. Therefore, the load carried by piles is reduced. The main purpose of providing pile raft foundation system is to improve the overall stability of the system, increase the load carrying capacity and decrease the amount of settlement of the foundation system. This study concentrates the load transfer mechanism from super structure to soil through the pile raft foundation system.

Many researchers have tried to present their thoughts on pile raft foundation. Irfan Jamil and Irshad Ahmad (2022) discussed combined piled raft foundation (CPRF) considering both raft and piles to take their share of the total load applied. Kumar and Choudhury (2015) showed the effect of pile head connection condition on the behavior of Combined Pile-Raft Foundation (CPRF) by using finite element based geotechnical program PLAXIS-3D. Azad Hameed Rasheed and Ola Adel Qasim (2020) conducted three-dimensional linear finite element investigation on pile raft foundation system and studied the load-settlement behaviour. They argued that raft size and pile length influence the performance of pile raft foundation system. Raj Banerjee and Srijit Bandyopadhyay (2020) reviewed the performance of pile raft foundation system in terms of serviceability and load-carrying capacity and investigated the settlement behaviour of a square-piled raft in a layered soil using numerical analysis. Venkataraman Balakumar and Huang (2019) studied the performance of combined piled raft foundation. According to them neither the pile group alone nor the raft by itself ensure the safety and the serviceability of the structure their support. It is the combined system that ensures the safety and serviceability of the structure. Hence a complete knowledge of the contribution of each element namely the pile, raft and the soil on the overall behavior is essential to generate an effective design. In spite of many attempts on the development in the area of pile raft foundation, there is scope for increased studies, especially to understand how the forces are transferred from super structure to soil through the complex medium of pile raft foundation which includes raft, individual piles and their interaction among themselves and with the soil they are in contact with.

2. PROBLEM STATEMENT

The focus of this paper has been to identify the mechanism of load transfer from superstructure to soil through medium of raft and piles. For this purpose, a pile-raft foundation system comprising of square raft of 9m side and thickness 0.5m along with 9 number of circular piles at equal spacing of 3m center to center both ways and length 20m is considered in a homogeneous clayey sand of thickness 75m with unit cohesion of 10kN/m^2, friction angle of 30^o and unit weight of 17 kN/m^3. The pile raft foundation is subjected to gradually increasing load from zero to failure. The displacements are restrained at the boundaries. The width of the pile raft foundation system is modeled to be 75m based on the consideration of boundary effect. It was found that any increase in width beyond 75m did not appreciably change the parameters such as stresses and deformations in pile raft foundation or adjoining soil. Further, convergence check showed that the 10-noded element size is sufficient. The effect of water table is not considered. Further, piles and raft are considered to be rigid and elastic and soil is modeled according to Mohr-Coulomb criteria. The loading is applied gradually on top of the raft till failure. Stresses in soil adjoining raft and pile and settlement in soil are studied for bringing out the mechanism of load transfer

To validate the numerical analysis in the present study, plate load test was simulated using circular plate. The ultimate load carried by the plate was assessed using Terzaghi's theory and compared with the present numerical tool. The results are tabulated in Table 1. It can be observed that this is a good assessment between the two results.

Table 1. Plate load test comparison findings for circular plates

Sl.No	Problem description	Ultimate Load From Terzaghi Theory in kN	Ultimate Load From PLAXIS in kN
1	C=35kN/m^2 Φ= 0^0 ϒ= 17kN/m^3 B=0.5m D=0.5m	53	60
2	C=10kN/m^2 Φ= 40^0 ϒ= 17kN/m^3 B=0.305m D=0.5m	152	161

Fig:01 Plate Load Test Result of Circular Plate

The contributions of pile and raft in carrying the total load is based on Finite Element approach using the software PLAXIS-3D. The 3-Dimensional model has been developed to consider the infinite soil system comprising of piles and raft. The objectives are to identify the stress in soil in different regions and settlement characteristics of Pile Raft foundation system.

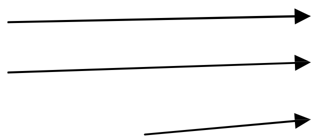

Fig. 2 PLAXIS 3D-Geometrical Model

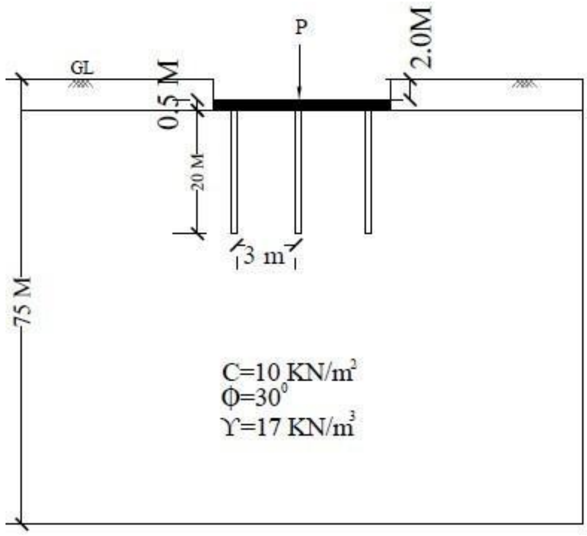

Fig. 3 Geometrical Model of Pile Raft Foundation system in homogeneous soil

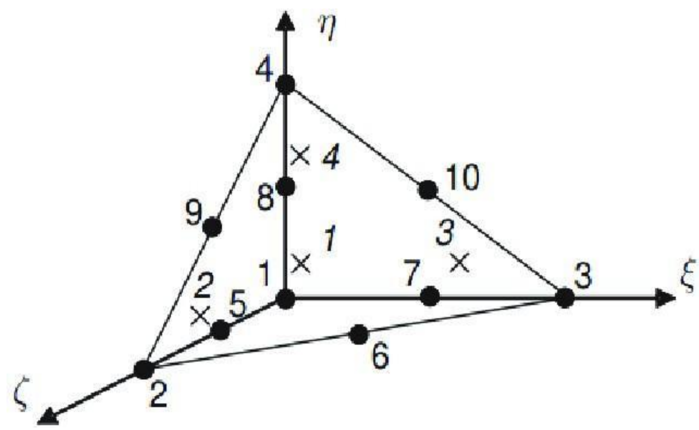

Fig. 4 Three-dimensional soil elements (10-noded tetrahedrons)

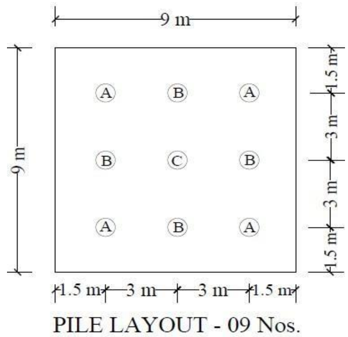

Fig. 5 Plan of Pile raft foundation system with pile types A, B and C

Fig.2 and Fig.3 present the geometric model of 3-dimensional pile raft foundation system. Fig.4 represents a three-dimensional soil element (10-noded tetrahedrons) which is used for the present work and Fig.5 represents the plan of the pile raft foundation indicating the locations of the pile and raft. It can be observed that there are three different types of pile, namely Pile type A, Pile type B and Pile type C. Pile type A are in the four corners, each having interaction with 3 piles. Pile type B are the four piles in the middle on the outer side, each having interaction with neighboring 5 piles and only one pile type C at the center which has a maximum interaction with 8 neighboring piles. It can be seen that the 9 piles have center to center spacing of 3 m both ways. Fig.6 presents the results of stress contour in different directions and locations. Table 2 gives the data values used in the present study to model soil, pile and raft. In the present study, no interface element is considered between pile and soil. Hence it is idealized that there is no slip between soil and pile surface during loading. For this purpose, interface strength reduction factor is considered as 1.

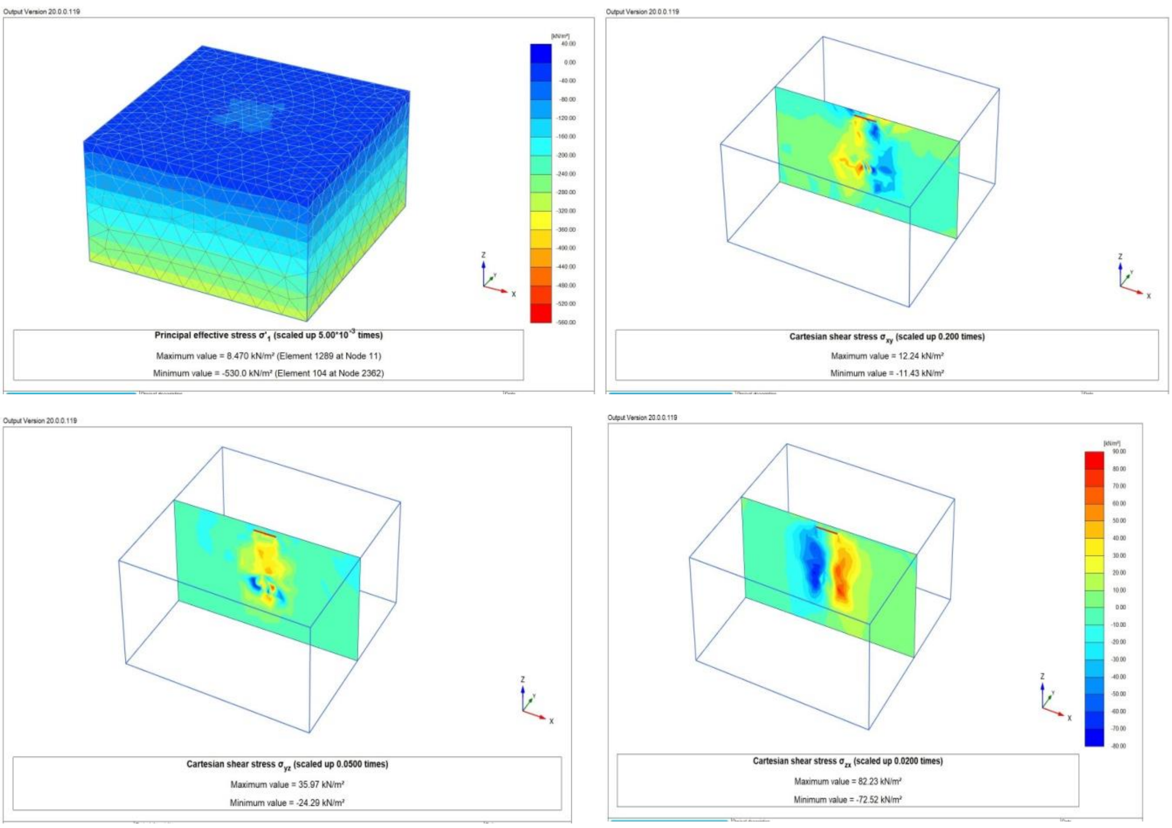

Fig.6 PLAXIS 3D-Effect of Stress in XY, YZ and XZ directions

Table 2. Properties of soil, Piles and Raft used in the present analysis

SOIL PROPERTIES		
Soil Type=	CLAYEY SAND	
Material Model =	Mohr-Coulomb	
Density γ =	17	kN/m^3
Young's Modulus E=	3000	kN/m^2
Poisson's Ratio μ=	0.3	
Cohesion C =	10	kN/m^2
Angle of Friction Φ=	30	^{o}
interface strength reduction factor (Rigid)	1.0	
PILE PROPERTIES		
Pile Diameter =	1.0	m
Young's Modulus E=	$20x10^6$	kN/m^2
Length of Pile=	20	m
Number of Piles=	9	Nos.
RAFT PROPERTIES		
Raft Size =	9.0 x9.0	m
Young's Modulus E=	$20x10^6$	kN/m^2
Density γ =	25	kN/m^3
Thickness=	0.5	m
Poisson's Ratio μ=	0.3	

3. MECHANISM OF LOAD TRANSFER

Pile raft foundation is a complex foundation system in which the interactions between raft and soil, pile and soil, pile and pile, raft and pile have to be seriously considered. Further, when the load is applied from the superstructure, the transfer of load through the foundation to the soil happens in a complex manner. To understand the mechanism of load transfer from superstructure to soil below, the stresses developed in soil and settlement experienced by foundation at different location under different loading conditions are carefully analysed in the present paper. For this purpose, the soil around the pile raft foundation is classified in to three regions as detailed in Fig.7. Region 1 is the zone exactly below the raft. The soil in this region is subjected to direct compression from top and hence the normal stress in vertical direction will be predominant. Region 2 is the zone of soil surrounding the piles along their length. The soil in this region is subjected to shear because of the interaction with pile. The challenge is whether the shear is fully mobilized and in which region the shear is fully mobilized. Further, Region 3 is the soil below the bottom of piles which is also subjected to compression under the pile. The same is presented in Table 3.

Table 3: Different zones in soil where the stress variations under increased loading are studied

Region 1	Portion of the soil just below the pile raft foundation
Region 2	Portion of the soil adhering to the surface of the pile along the length of the pile experiencing shear stress
Region 3	Portion of the soil below the bottom of the pile

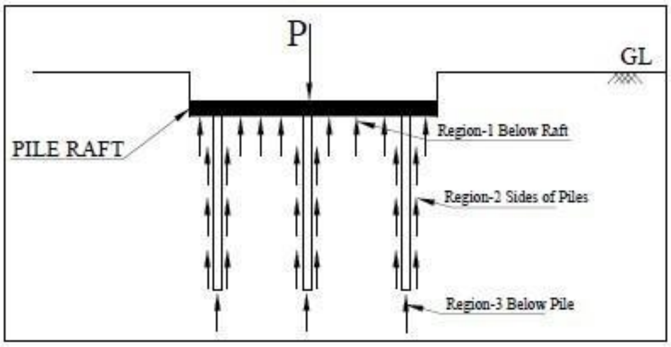

Fig.7 Pile-Raft foundation system

Stresses in Soil in Region 1

In order to make sure about the stress development in soil below the base of raft, Fig.8 indicates the sections along which the vertical normal stress and corresponding vertical settlement are plotted. Sections A-A to E-E are in Y direction and sections 1-1 to 5-5 are in X direction. Fig.9 indicates the distribution of normal stress from section A-A to E-E. It can be seen that the stresses start to increase from the ends and are transferred towards the centre. With increase in load the stresses increase near the end and the amount of increase near the centre is nearly insignificant. At the final load, stresses are close to zero near the centre and maximum along the edges. If at all failure happens, soil yields from near the edge towards the centre. Fig.10 and Fig.11 indicate the distribution of settlements along different sections in both the directions. It can be seen that the settlement is maximum near the centre and reduces towards the edges. The trend is similar in both the directions. Further, the central sections C-C and 3-3 experience the maximum settlement and the settlement reduces towards the edges. It may be seen that the stresses and displacement are not symmetric even though the loading and geometry are symmetrical. This variation is because the points chosen for stress and displacement determination are not exactly at the same elevations and locations on the two sides.

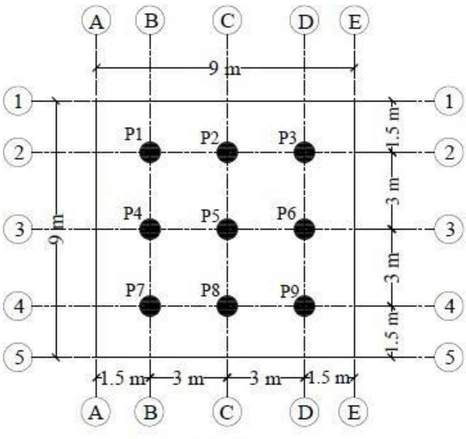

Fig.8 Plan of pile layout with sections 1-1 to 5-5 and A-A to E-E

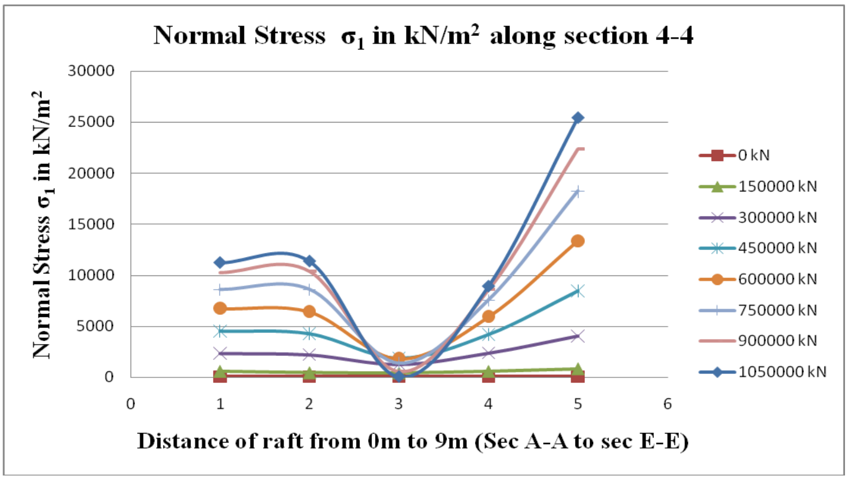

Fig.9 Effect of normal Stress below the raft at section 4-4 for different loading conditions

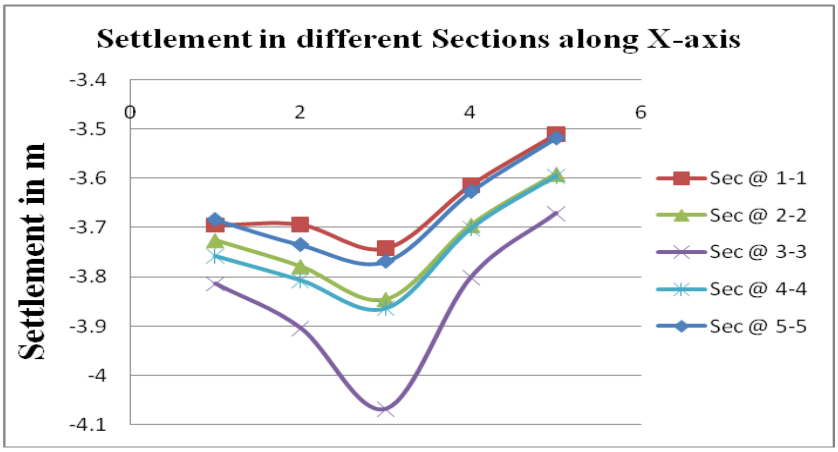

Fig.10 Maximum Settlement below the raft for different sections along x-direction

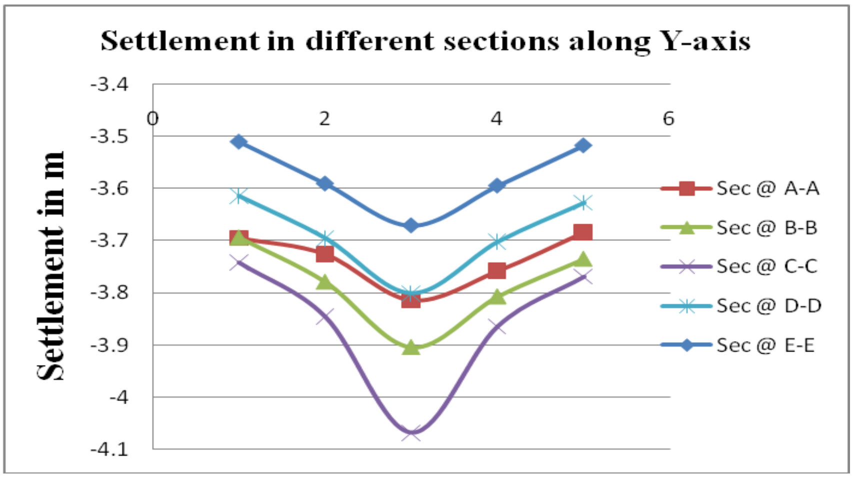

Fig.11 Maximum Settlement in different sections along Y-direction

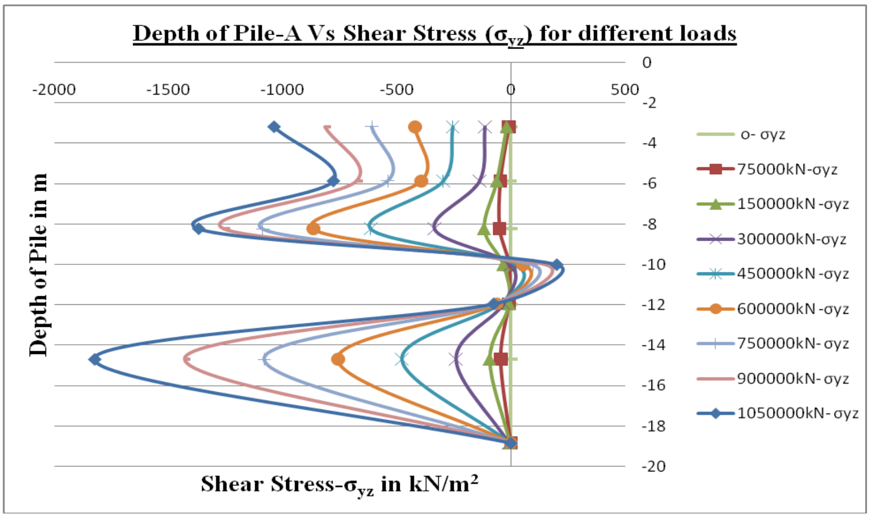

Fig.12 Effect of Shear Stress in YZ-direction for pile type-A

Stresses in Soil in Region 2

Fig.12, Fig.13 and Fig.14 are plotted for Pile Types A, B and C respectively. It is interesting that the maximum shear stress is experienced in the soil surrounding edge pile of type A which has minimum interaction with neighboring piles (only 3 neighboring piles interact). As seen in Fig.12. The stresses start mobilizing from top, reach a maximum value near the top and transfer the peak stress towards the bottom with increase in load. The maximum shear stress develops near the bottom towards failure stage. The shear stress pattern is changed near the center of pile along the length. Fig.13 shows the variation in shear stress along the length of pile with increase in load for pile type B. It is interesting that there is a reduction in peak value (magnitude) of shear stress as compared to those of pile type A. Shear stresses are more near the bottom compared to the case of pile type A. But the peak is near the top.

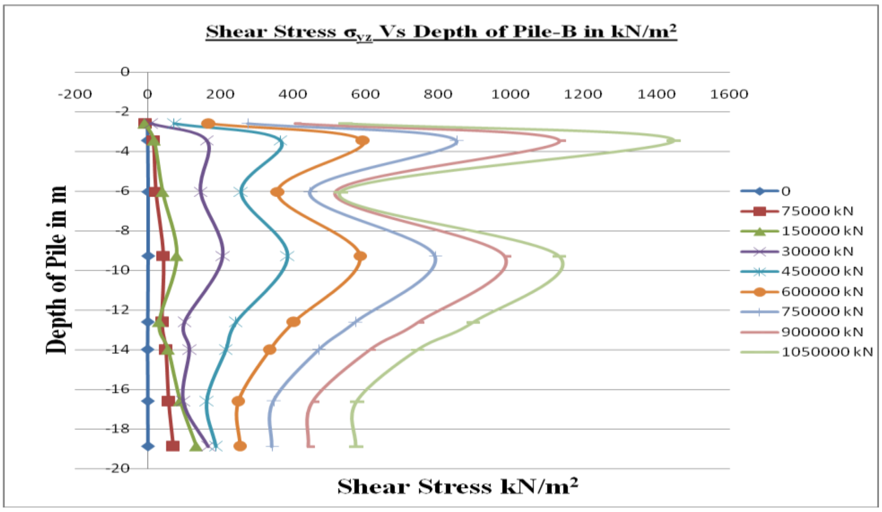

Fig.13 Effect of Stress in YZ-direction for pile type-B

Fig.14 shows the variation in shear stress in soil along the length of pile of type C at the center with increase in load. This pile has maximum interaction with all piles. However, because it is at the center, the interaction is well balanced and hence the peak shear stress is much smaller than that observed for cases of pile types A and B. The two ends are subjected to least values and the maximum is near the top. The signs of shear stress are different at top and bottom.

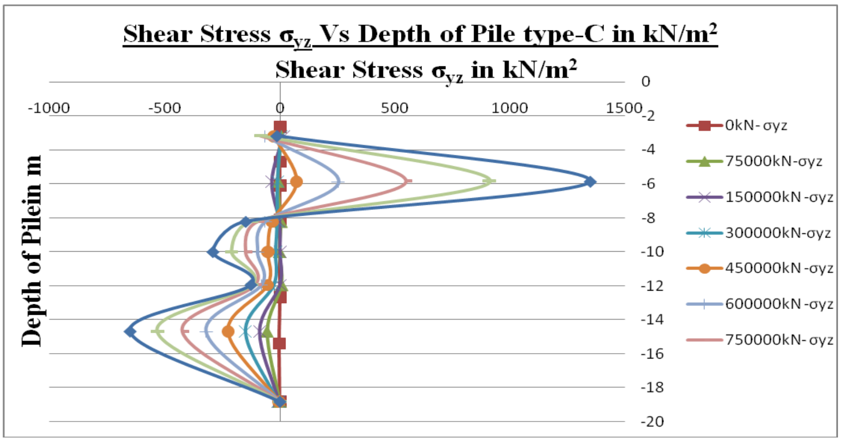

Fig.14 Effect of Stress in YZ-direction for pile type-C

Stresses in Soil in Region 3

Fig.15 presents the normal stress distribution at the pile tips with increasing loads for all the three types of piles A, B and C. With increase in load the magnitude of normal stress increases. The rate of increase is the maximum in the beginning and gradually decreases towards the end. Middle pile is subjected to maximum normal stress and the edge piles are subjected to lower values.

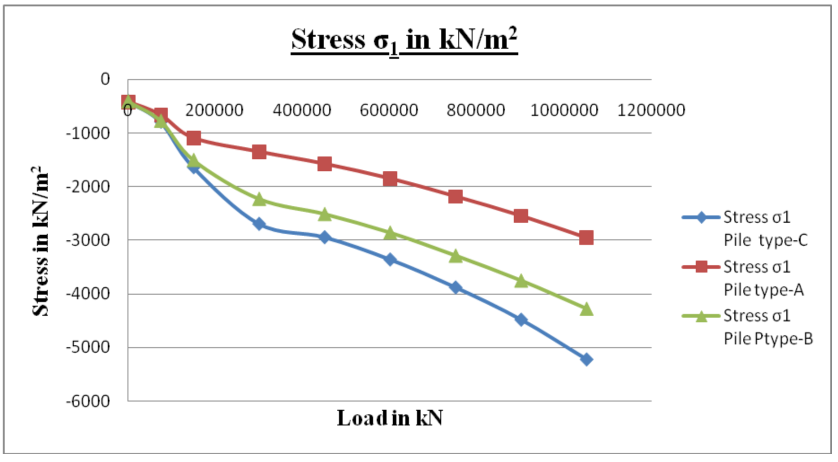

Fig.15 Effect of Stress σ_1 for pile type-A, B and C

From the present study the following understanding can be made with regard to transfer of forces from foundation to the soil.

The pile raft foundation is sufficiently stiff compared to the surrounding soil. The load transfer first takes place from the raft to the soil around. Simultaneously the bottom of the pile also transfers the stresses to the soil. The rate at which the force is transferred at the base of pile is more in the beginning and gradually it decreases with increasing load. Then, the load transfer happens along the surface of pile. This transfer is mainly due to shear and it appears that the transfer happens near the top at the start and gradually it is transferred towards the bottom. The biggest challenge is whether the shear is completely mobilized. The effectiveness of pile depends on the mobilization of shear.

Concluding Remarks

The load transfer mechanism from foundation to soil in pile raft foundation is a complex phenomenon because of the involvement of many foundation components in different regions. It should be noted that the interaction between raft and soil, pile and soil, pile and pile and pile and raft should be carefully understood. Further, the performance with increase in load can be very different because of non-linear behavior of soil, changes in interaction in different components and many other factors. An attempt is made to explain the load transfer mechanism from pile raft to soil in a homogeneous soil. The foundation is subjected to increasing concentric vertical load from zero till failure. The foundation is considered to be rigid and elastic and soil is deformable and behavior of soil is non-linear. From the present work, the following inferences are made.

- The load transfer takes place due to compression at the top near the raft and at bottom near the bottom tip of piles.
- The rate of load transfer is more in the beginning near the bottom tip of pile and gradually it decreases.
- The stresses developed are more near the edge than the center in the soil below the raft. Hence load transfer gradually increases from edges towards center.
- The load transfer is mainly through shear along the surface of piles. The transfer starts from the top and gradually increases towards the bottom.
- The soil in the zones near the central pile is subjected to less shear stress compared to that near the piles at the ends.
- However, the compressive stress in soil at the base is more near the central pile than that at the edge piles.

The performance of pile raft foundation system completely depends on how the shear is mobilized along the length of pile. The overall load carrying capacity and settlement control completely depend on this aspect. Hence, number of piles used, pile size and length of pile also significantly influence the overall performance.

References:

1. Irfan Jamil and Irshad Ahmad (2022) "Analysis and Design of Piled Raft Foundation Taking into Account Interaction Factors", Advances in Civil Engineering, Volume 2022, Article ID 1334136, 11 pages https://doi.org/10.1155/2022/1334136

2. Kumar A and Choudhury D (2015) "Behaviour of Combined Pile-Raft Foundation (CPRF) under Static and Pseudo-static Conditions using PLAXIS3D", 6th International Conference on Earthquake Geotechnical Engineering, 1-4 November 2015, Christchurch, New Zealand

3. Azad Hameed Rasheed and Ola Adel Qasim (2020) "Behavior of Pile Rafts with Raft Size, Number of Piles and Different Pile Length", AIP Conference Proceedings 2213, 020196 (2020); https://doi.org/10.1063/5.0000211, Published Online: 25 March 2020

4. Raj Banerjee and Srijit Bandyopadhyay (2020) "Settlement behaviour of a pile raft subjected to vertical loadings in multilayered soil", ISSN: 1748-6025 (Print) 1748-6033 (Online) homepage: https://www.tandfonline.com/loi/tgeo20

5. Venkataraman Balakumar and Huang M et. all, (2019) "Behavior and performance of piled raft – A comprehensive study", Proceeding of 16th Asian regional conference on Soil mechanics and Geotechnical engineering, Oct 14-18 2019, Taipei, Taiwan: http://seags.ait.asia/16arc-proceedings/16arc-proceedings/